COALESCENCE OF A STRANGE STAR WITH A BLACK HOLE

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ABSTRACT

We present the first numerical results on the binary coalescence of a quark star with a black hole, obtained with a 3-D Newtonian smooth particle hydro (SPH) code. The star is initially represented by 17,000 particles modeling a self–gravitating fluid with the equation of state $P = (\rho - \rho_0)c^2/3$, and the black hole by a point mass with an absorbing boundary at the Schwarzschild radius. As in similar calculations carried out for a stiff polytrope, the stellar core survives the initial episode of mass transfer, but here an accretion disk is clearly formed as well.

1. INTRODUCTION

Binary coalescence of compact objects must give rise to gravitational radiation emission which is expected to be observed with such instruments as LIGO or Thorne 1995). Neutron stars co-VIRGO (e.g. alescing with black holes may also be the source of r-process nuclei and of gamma-ray bursts (Lattimer and Schramm 1976). Coalescence of any compact objects (black holes, neutron stars, quark stars) may release enough energy to power a fireball giving rise to some cosmological gamma-ray bursts (Paczyński 1986), and the coalescence of strange (quark) stars may be especially promising (Haensel et al. 1991), provided that no quark matter is spilled into the environment with dire consequences for the birth rate of neutron stars (Caldwell and Friedman 1991, Kluźniak 1994).

More detailed motivation and further references can be found in Lee and Kluźniak (1999a), where the SPH coalescence of a tidally locked neutron star and a black hole is discussed. Lee and Kluźniak (1999b) discuss the coalescence of a tidally locked stiff polytrope with a black hole, while SPH simulations of non-rotating neutron stars in binary coalescence with black holes have been presented by Lee (2000).

2. NUMERICAL METHOD AND INITIAL CONDITIONS

We have used the Smooth Particle Hydrodynamics (SPH) method (Monaghan 1992) for our calculations. Our Newtonian code is three dimensional and we include a term in the equations of motion that simulates the loss of angular momentum to gravitational radiation in the binary (this is calculated in the quadrupole approximation for a point-mass binary). We also compute the gravitational radiation waveforms emitted during the coalesence, in the quadrupole approximation. The strange star is modeled with N = 17000 SPH particles, and has mass $M_{SS} = 1.4 M_{\odot}$ and radius $R_{SS} = 11$ km. The black hole is modeled as a point mass producing a Newtonian potential, and we model accretion onto it by placing an absorbing boundary at the Schwarzschild radius $r_{Sch} = 2GM_{BH}/c^2$. For the strange star we take the equation of state to be $P = c^2(\rho - \rho_0)/3$, with $\rho_0 = 5 \times 10^{17} \text{ kg m}^{-3}$.

To perform a dynamical coalescence calculation, we place the binary components in a close Keplerian orbit at a small separation (a few stellar radii) and give them the corresponding orbital velocities for point masses. The strange star is initially spherical and has no spin as seen from an external, inertial reference frame. The orbit decays through the emission of gravitational waves and because of tidal instabilites of purely Newtonian origin (Lai, Rasio & Shapiro 1993).

Here we present the result of one calculation, with an initial mass ratio $q = M_{SS}/M_{BH} = 0.3$ and initial separation $r_i = 3R_{SS}$. The dynamical evolution of the system is followed for approximately 7 ms.

3. RESULTS

At the start of the simulation a tidal bulge appears on the strange star as a result of the presence of the black hole companion. The orbital decay causes the star to overflow its Roche lobe, beginning mass

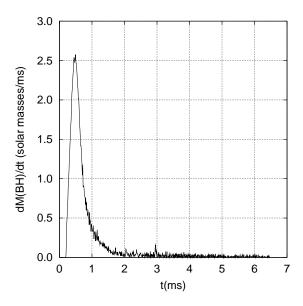


Figure 1. Mass accretion rate onto the black hole as a function of time.

transfer within the first orbit. The star is tidally stretched into a tube of practically uniform thickness, and some matter that moves towards the black hole winds around it and produces a torus (see Figure 1). The outer parts of the star move away from the hole as the stream connecting the two becomes thinner. Small condensations form at regular intervals along the narrow stream (see panel (d) in Figure 1), reminiscent of the results of a black hole—neutron star coalescence for a stiff equation of state (Lee 2000).

The mass accretion rate onto the black hole shows a large initial peak at the initial mass transfer episode (see Figure 2), and a subsequent decay, due to the presence of the accretion torus. The small spikes in the curve (such as the ones visible at $t \simeq 2.1, 2.4, 3$ ms) indicate the accretion of small knots along the matter stream coming from the star.

In the accretion disk around the black hole, the density has dropped below ρ_0 and so this matter behaves as pressure—free dust in orbit about the hole (for reference, in Figure 1 $\log(\rho_0/\rho_*) = -0.62$). However, in the surviving core, flung to a large distance during the tidal encounter, and in the small condensations seen in the matter stream connecting the two binary components, the density remains above this value, and thus the matter continues to feel hydrodynamic effects. By $t \simeq 5$ ms, there are 0.15 solar masses in the system excluding the black hole, and this is roughly evenly divided between matter with densities above and below ρ_0 .

4. DISCUSSION AND CONCLUSIONS

At the end of the calculation we have attempted to obtain an estimate for the amount matter that could be dynamically ejected from the system, by computing the total mechanical energy (kinetic + gravitational potential) of the fluid. We find that $5 \times 10^{-3} M_{\odot}$ could leave the system, and would originate from the outermost section of the largest blob formed at the end of the tidal tail. The rest of the matter $(0.15 \ M_{\odot})$ is gravitationally bound to the black hole, located practically at the center of mass of the system, and which has acquired a kick velocity from the asymmetric interaction $(v_{kick} \simeq 10^3 {\rm km \ s^{-1}})$.

Some of the matter in the accretion torus has enough angular momentum so as not to be accreted immediatly by the black hole (i.e. it can remain in orbit in a stable fashion), amounting to $0.08M_{\odot}$. This fluid would presumably be accreted onto the black hole on the viscous time scale as angular momentum is redistributed in the disk.

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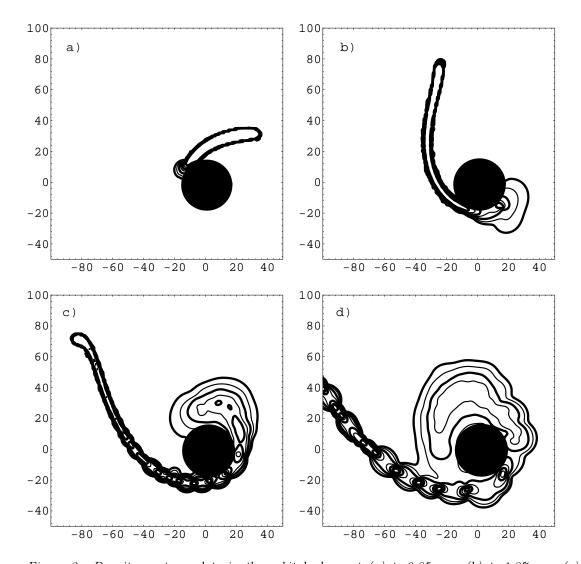


Figure 2. Density contour plots in the orbital plane at (a) t=0.85 ms; (b) t=1.27 ms; (c) t=1.7 ms; (d) t=2.12 ms. The axes are labeled in km. All contours are logarithmic and equally spaced every 0.5 dex. Bold contours are plotted at $\log(\rho/\rho_*) = -4, -3, -2, -1$ (with $\rho_* = M_{SS}/R_{SS}^3 = 2.08 \times 10^{18}$ kg m⁻³).